DEVELOPMENT OF A 100 WATT S-BAND TRAVELING-WAVE TUBE

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ABSTRACT

This report is the second quarterly progress report on the development of a 100 watt, 55 percent efficiency 2.3 GHz traveling-wave tube for space applications. During this quarter, three tubes were built. These tubes were designed as simple, single helix tubes to work out the basic electrical, mechanical, and beam focusing problems. In addition, RF performance evaluations were made to determine if the performance correlated with design calculations. The evaluation of the third tube was not complete at the end of this quarter, but its performance has shown up to 120 watts power output. Detailed RF performance characteristics for the three tubes are given. The test vehicle for the high efficiency studies has essentially been established.

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I. PURPOSE AND GOALS OF THE PROJECT

The purpose of this program is to develop a high efficiency 100 watt 2.3 GHz traveling-wave tube suitable for use in space. The tube has been designated the WJ-395. The most important goal of the program, requiring an advance over present techniques, is the achievement of high efficiency. The basic performance goals are a power output of 100 watts at an overall efficiency of 55 percent and a gain of 30 dB. Other requirements dictate conduction cooling and the ability to perform through launch and under space environment conditions.

At the time of the contract award, excellent results had been achieved on a study program directed toward the design of high efficiency traveling-wave tubes at Watkins-Johnson. This program, supported by the Evans Laboratory of the U.S. Army Electronics Command under Contract No. DA-28-043AMC-02004(E) had been underway for some time. In the course of the ECOM program, a helix type traveling-wave tube was built which yielded an overall efficiency of 51 percent with 20 watts output at 1.0 GHz. This was done using a "two helix approach" wherein a signal was amplified and extracted from a first section of the tube and reinserted into an attenuatorless helix section at the output which could be operated at a different voltage. The output signal of the tube is taken from the second helix section and the electron beam is collected at a reduced potential in a depressed collector to minimize the dissipation of the beam energy as much as possible. The electron beams on these tubes were focused with solenoidal magnetic fields.

This present program to develop a 100 watt tube at 2.3 GHz is planned to apply the above efficiency improvement techniques to PPM focused TWT's. This program is intended to produce actual hardware for space flights.

II. TUBE CONSTRUCTION AND PERFORMANCE

Purpose of Early Tubes

It was decided that the first tubes to be built would be "single helix" tubes as distinguished from "two helix" tubes. In other words, they would be conventional traveling-wave tubes with input and output helix sections separated by an attenuator. This would allow the basic mechanical designs to be refined. Also the power handling capability of the tube at the 100 watt level could be verified and the thermal design of helix and collector could be developed. It would also allow experimentation with the magnetic field programs in a simple magnet configuration without the added complication of special magnet cells in the sever region between the first and second helix sections. These early tubes could also be used in preliminary environmental testing to give information as to the adequacy of the mechanical and thermal design.

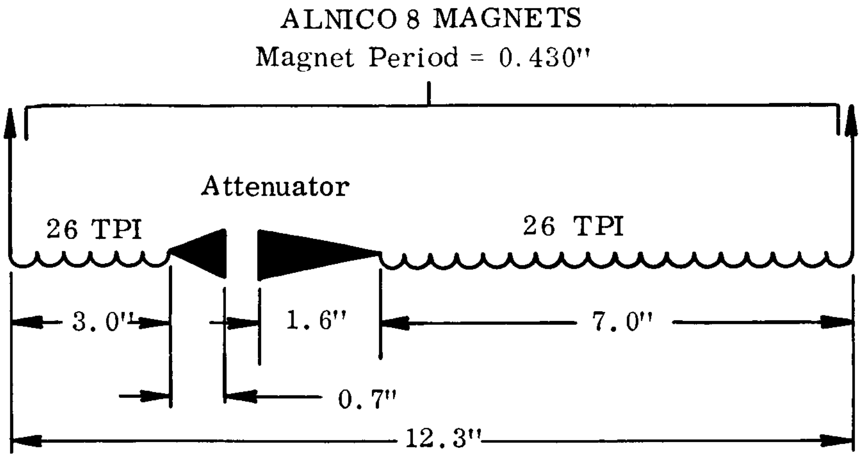
Tube 1: WJ-395 SN/1

As described in Quarterly Project Report No. 1, the design of the interim tube was based upon an assumed basic beam efficiency of 30 percent and large overvoltage operation. The helix, magnet array and attenuator in schematic form of SN/1 is given in Figure 1. The beam, helix, and other design parameters are given in Table II of Quarterly Project Report No. 1. The magnet stack was designed to use Alnico 8 magnets. Magnets were ordered from two vendors early in the program, but are long delivery items. These magnets had not been delivered at the time that tube No. 1 was ready for test. It was necessary to substitute a temporary set of magnets made by grinding some off-the-shelf magnets of approximately the right size that were available from another supplier. Since the temporary magnets were thinner than those required for a single cell, it was necessary to grind each magnet to one-half thickness and use two magnets of the same polarity in each cell. Since the magnets were also split in half across their diameter, it was necessary to have four magnet pieces in each cell which made the magnets very difficult to handle. This type of magnet array exhibited effects which suggested the presence of appreciable transverse magnetic field in the individual cells. Because of these effects, adjustment of the magnet system for good focusing was difficult.

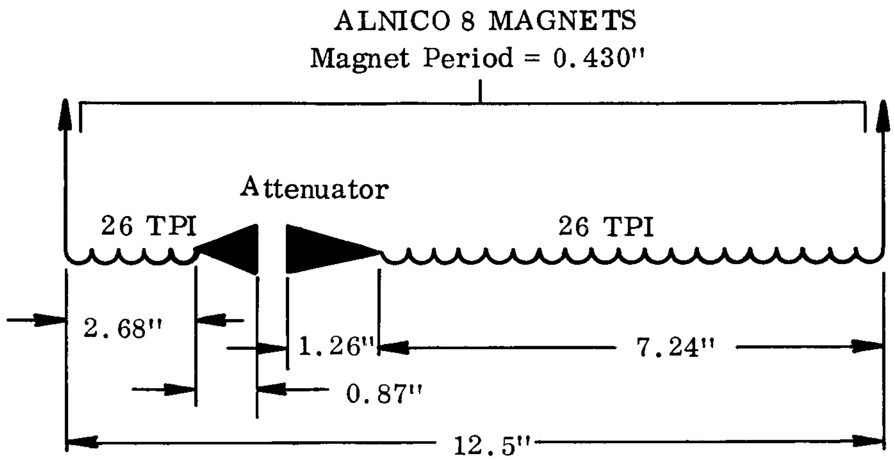
SN/1 was constructed, pumped and placed in test. Initial focusing and RF tests were made under pulsed conditions. After satisfactory focusing was achieved, all subsequent tests were made under CW conditions.

Performance of the tube was well below design levels. Under conditions where the tube should have given 100 watts, a maximum of 30 watts was achieved. Beam efficiency was measured at a maximum of 10 percent. Detailed performance plots of power output, saturation gain and beam efficiency vs. helix voltage are shown in Figure 2. A power transfer characteristic and a plot of power output vs. frequency are shown in Figure 3.

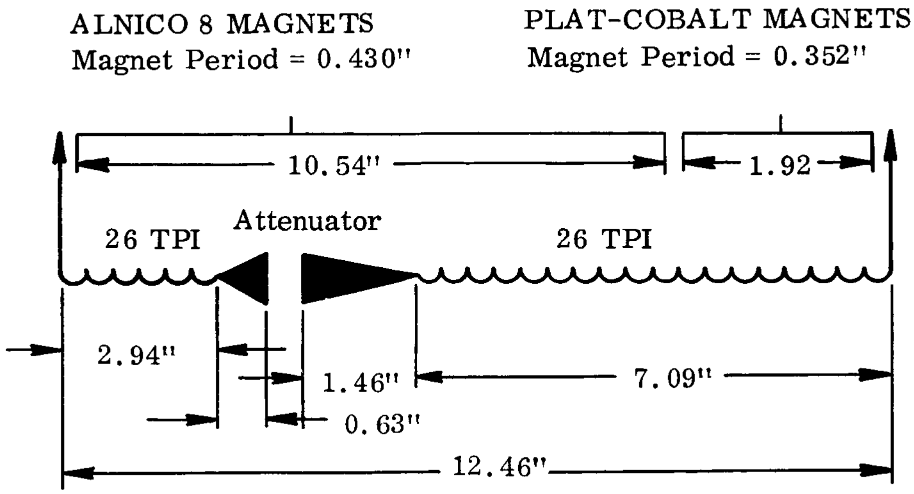
Examination of Figure 2 shows, in general, the characteristics of an overvoltaged tube. Power output and efficiency increase with helix voltage, and saturation gain decreases as almost a linear function (in dB) of helix voltage. With beam



Tube No. 1



Tube No. 2



Tube No. 3

Fig. 1 - Helix, Magnet and Attenuator Configuration for Tubes Serial Nos. 1, 2 & 3.

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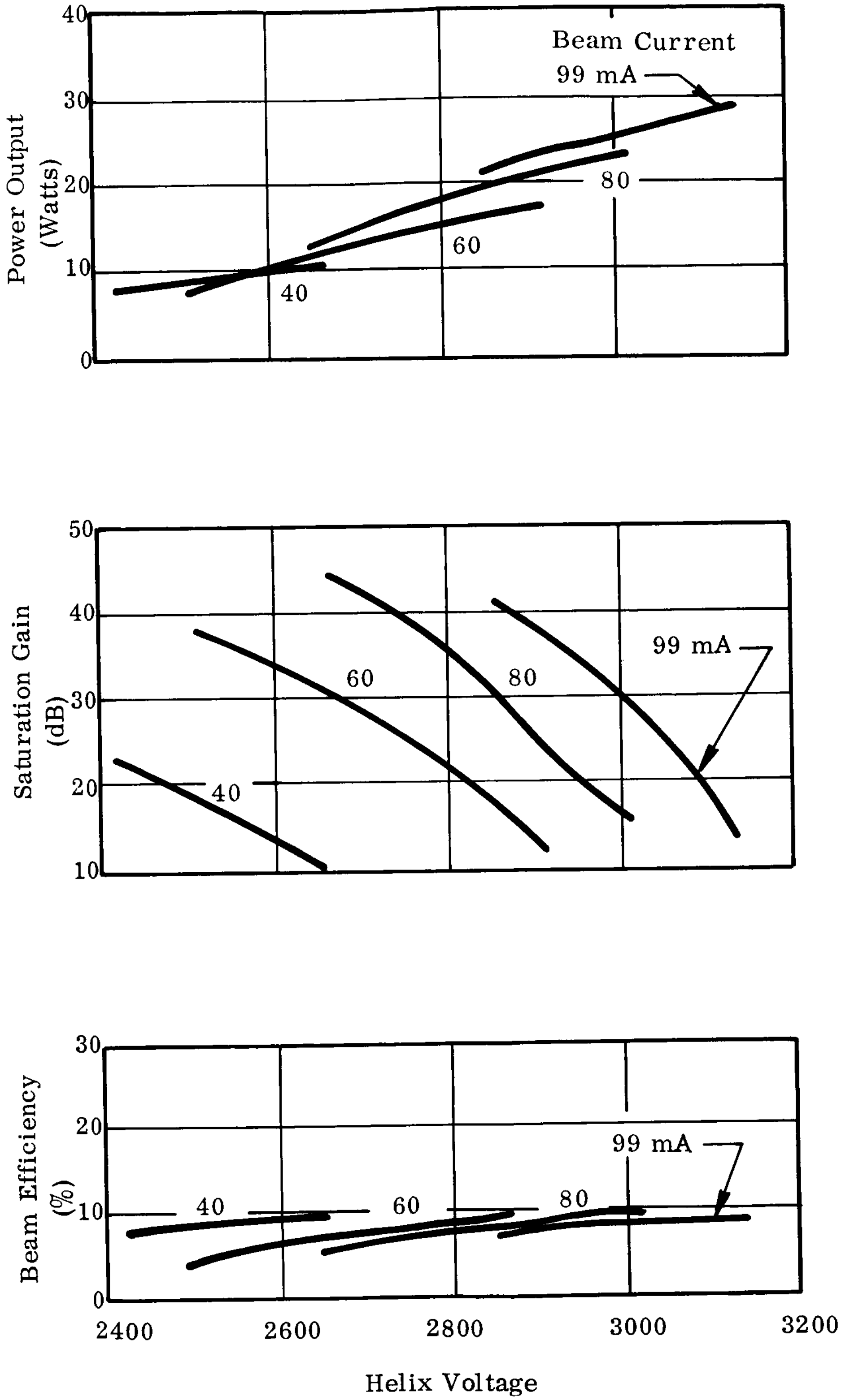
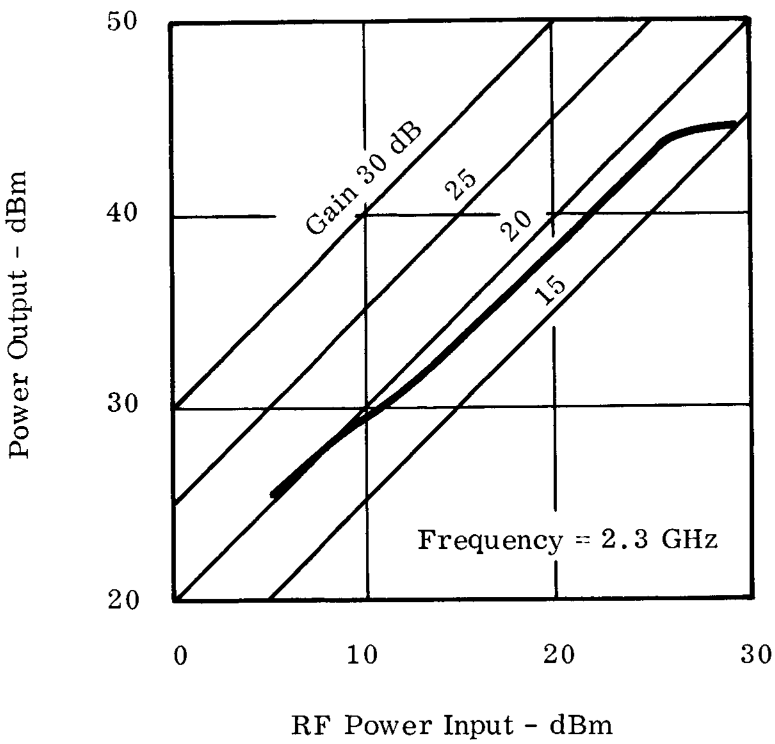


Fig. 2 - Saturation Power Output Gain and Beam Efficiency of WJ-395 No. 1 at 2300 MHz.



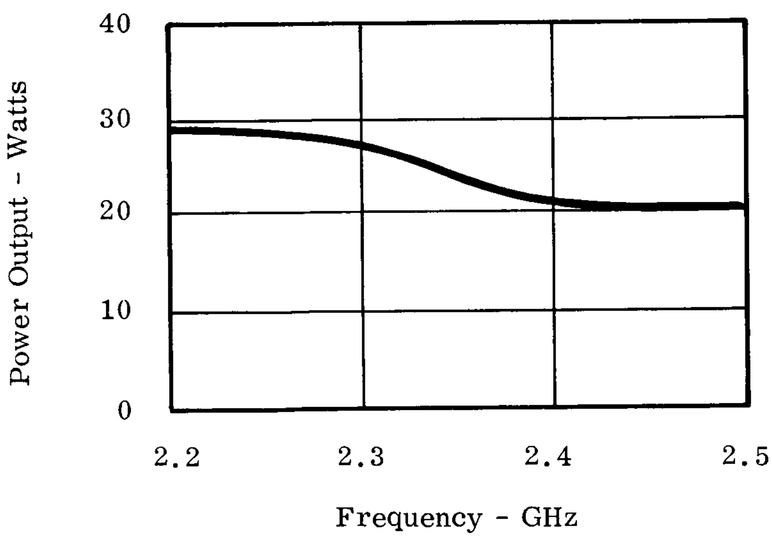


Fig. 3 - Plots of WJ-395 No. 1 data showing transfer characteristic and broadband power performance at V_{helix}= 3135 V and a beam current of 98 mA.

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current as the parameter, the curves successively move into the region of higher voltage operation. The beam efficiency curves limit out at a value of approximately 10 percent, which is far below the expected value. This is discussed in more detail below. Figure 3 shows a plot of power output vs. power input. The shape of this curve, which shows a small signal gain 3 to 5 dB greater than saturation gain, indicates that the tube is not operating properly under large overvoltage conditions and therefore efficiency will not be very high. Also in Figure 3 is shown a broadband characteristic across the range of 2.2 to 2.5 GHz. Power is low because the tube efficiency is so low. It does show potential broadband characteristics, however.

It was noticed that the output region over an extended distance was exceptionally warm under RF drive. This would indicate that the helix is excessively lossy in this region. Other performance of the tube tended to corroborate the idea that the helix was very lossy. This loss in turn would lead to lower efficiency than expected. Apparently, the helix support rods had become coated with a lossy film. This probably occurred during a vacuum firing that was given to the body with the helix assembly clamped inside or possibly it could have been caused by a chemical cleaning that was given prior to the vacuum firing. Another possible cause of low efficiency was the possibility of a non-uniform helix. This was unlikely, however, because of the assembly technique that is used. The most likely cause of the low efficiency is helix loss, and extreme care will be exercised in the assembly of the subsequent tubes.

Focusing was good, with dc transmission of the electron beam to the collector of 99 percent. Under RF drive, beam transmission greater than 90 percent was achieved, which is good for this early development stage with no focusing refinements yet accomplished. It was felt that it would be too difficult to attempt to program the magnet stack with its multisegment magnets for an optimum field value. The magnets were all magnetized to their saturated value and were used without further adjustment. This probably led to an excessive magnetic field, which in turn would cause a higher than normal helix interception under saturated RF drive conditions.

The collector design seemed to perform satisfactorily under laboratory conditions with air cooling fins attached. The appendage pump tabulation is attached to the center of the collector on this tube, and it contributed to the collector cooling.

Conclusions on SN/1

It was realized from the data that SN/1 was performing far below expectation because of probable helix loss and that another tube of essentially the same design should be built. Construction of the next tube would be altered to correct the problems which were believed to have caused the difficulty. Another limitation on the testing of SN/1 was the power supply. The powe r supply which had been ordered for testing of the WJ-395 had not arrived and a substitute supply had to be used. The substitute supply was limited to 100 mA on the collector current supply. This prevented higher current data from being taken. However, in light of the observed performance, efficiency would not have improved under higher current conditions.

Tube 2: WJ-395 SN/2

The design of SN/2 was essentially the same as SN/1, given in Figure 1. It was still necessary to test SN/2 under the handicap of the temporary magnets and the power supply with the limited collector current capacity. Neither special magnets nor the power supply had arrived yet. It was found possible to increase the power supply current to 110 mA before its overcurrent trip-out would trigger the power supply crowbar, turning off the supply. It was still felt that any attempt to adjust the magnetic field on the tube to a more optimum program would be too tedious with the temporary magnets. Thus, these tests were made with the magnets individually saturated and this accounts for the previously used peak value of magnetic field of 1200 gauss.

Figure 4 shows a plot of power output, saturation gain, and beam efficiency vs. helix voltage used to evaluate the basic performance of the tubes under over-voltage operation. Superimposed on the curves showing saturation gain are curves showing small signal gain as a function of helix voltage. The power and efficiency curves are beginning to show characteristics expected in the region of high efficiency performance. Note the upturn in the slope of power output above 3000 volts at beam currents of 100 mA or greater. This same upward slope is also in the efficiency curves although it is not so apparent on the vertical scale to which efficiency is plotted. The tube is not operating under the optimum magnetic field conditions, nor can the beam current be increased sufficiently (because of the power supply limitation) to extend the beam efficiency beyond 20 percent. However, all indications are that much higher performance could be achieved. Note that a power output of 75 watts was reached.

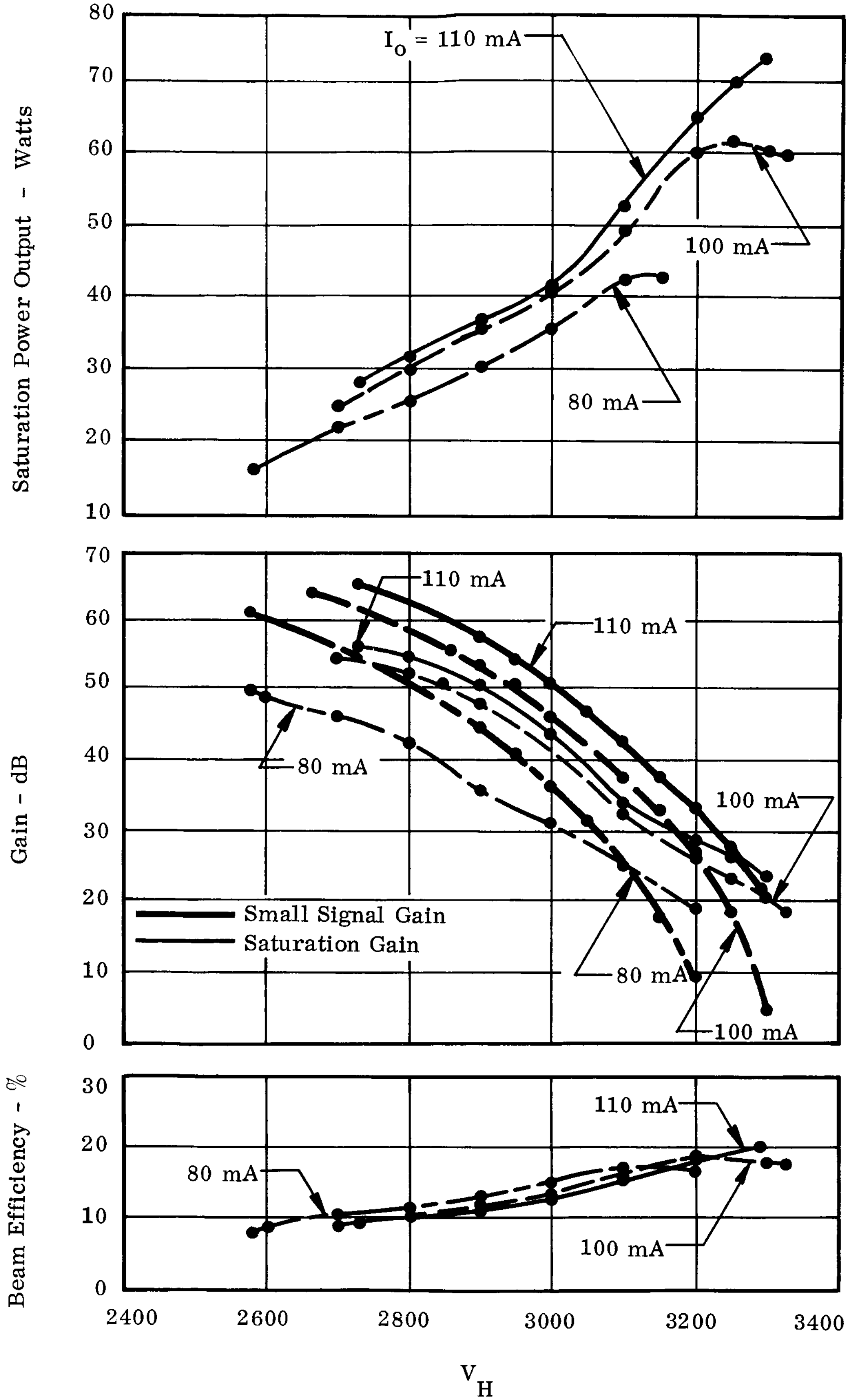

Fig. 4 - Saturation power output, gain, and beam efficiency of WJ-395 No. 2 at 2300 MHz.

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Focusing performance was much the same as in SN/1. Transmission under dc conditions was 99 percent and under saturated RF conditions was 90 percent. Again no work had been done to optimize the average peak magnetic field.

Figure 5 shows a power transfer characteristic under the beam conditions of 3292 volts and 110 mA. This shows the rising gain characteristic of over-voltage operation. In this case saturation gain is 24 dB and small signal gain is 21 dB.

At a later time, a power supply was borrowed, which could operate at higher currents. Just as tests were about to begin, a metal-ceramic seal in the collector opened up and the tube went down to air. Subsequent examination of the seal determined that brazing alloy had not properly flowed during construction of the collector. Subsequently design changes were made to correct this problem.

SN/2 was later reprocessed as SN/2B with a new collector and gun. Its RF performance after reprocessing was much inferior to the data of Figures 4 and 5. The exact cause of this was not determined, but it is likely that loss was deposited on the output helix.

Conclusions from Tests on SN/2

Several conclusions about the electrical and mechanical design were arrived at after testing of SN/2. In terms of the electrical design, the following evaluation was made:

1. The basic electrical design had not been proven out yet, in that only 20.5 percent beam efficiency had been achieved instead of the 30 percent design value, and only 76 watts of power output had been realized. It was felt that another single helix tube should be built to complete the evaluation of the design as a test vehicle for more complex designs.

In terms of the mechanical design, the following evaluations were made:

1. The heater power required was about twice what was expected. It was realized that the crossed-rod cathode support structure was causing an excess heat conduction loss from the cathode. This was determined by the gun ceramic configuration and could not be improved without modifying this major assembly. The decision was made to change the cathode support to a thin metal sleeve.

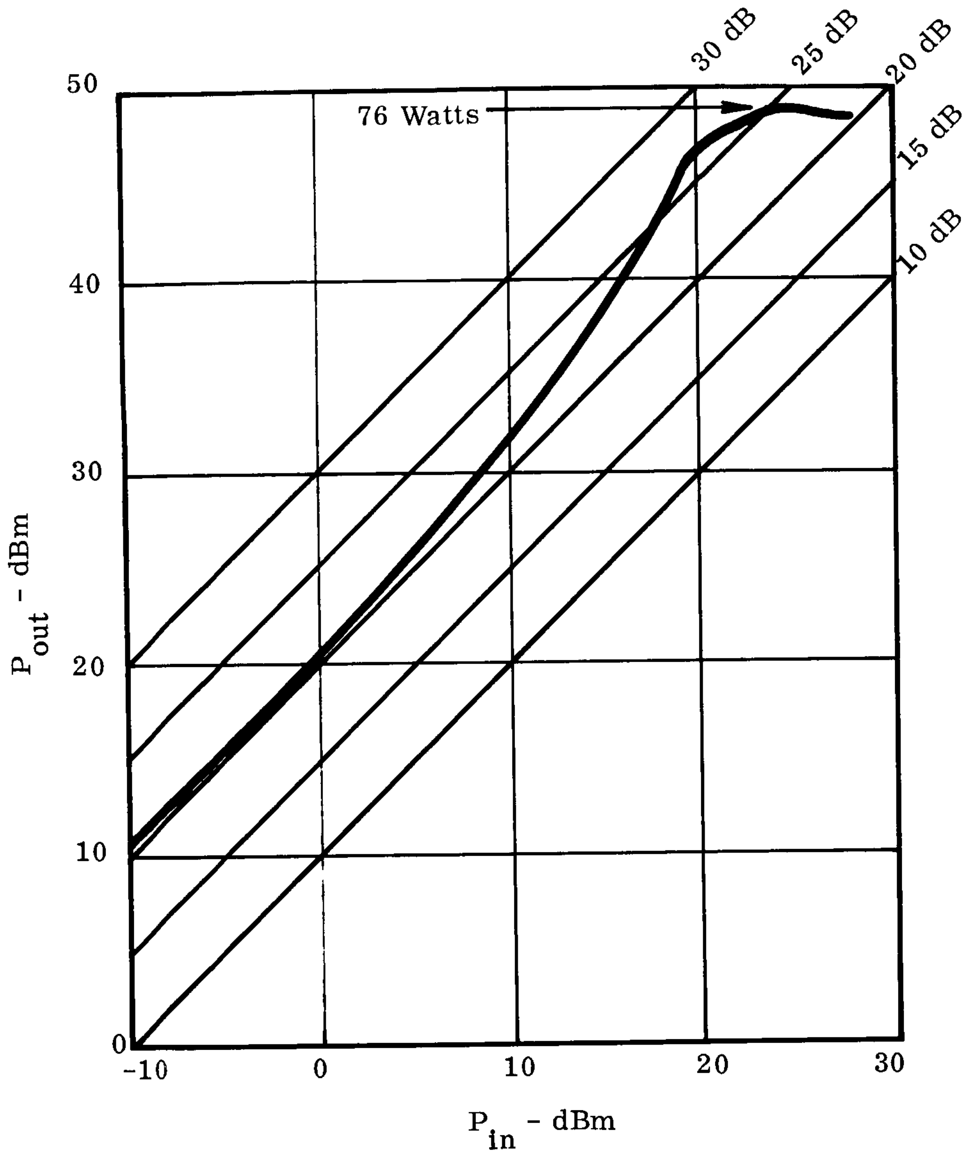

Fig. 5 - Power output vs. power input of WJ-395 no. 2 at 2300 MHz. Helix voltage = 3292 volts. Beam current = 110 mA.

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2. The appendage pump was attached to the tube through the collector on tube SN/1 and SN/2. It was decided to change this to the gun end of the tube to remove possible mechanical strain from the collector seals during testing. This removed part of the heat dissipation path from the collector so that it was necessary to modify the collector to allow additional cooling fins to be added for lab testing.

Gun Test Structure

An electron gun was built with the new sleeve-supported cathode. The gun test structure was built with an optical window so that the cathode temperature could be measured pyrometrically. Correct cathode operating temperature range was measured with 3.5 to 4.0 watts heater power, an acceptable range.

Tube 3 - WJ-395 SN/3

The original intention for the design of SN/3 was to use a glazed helix. This was to test out a hypothesis that the clamped helix structure allowed non-uniformities to creep into the helix structure during helix insertion or later assembly operations and processing which in turn could degrade tube efficiency. This is in contrast to the glazed helix which holds the helix pitch uniformity to precisely the "as wound" value. High beam efficiencies had been observed on other tube types using glazed helices, while high beam efficiencies had not been observed using clamped helix structures. However, constructional problems were encountered in making a glazed helix for the WJ-395 even though glazed helix construction is common practice at WJ. To avoid further loss of time, it finally was decided to make SN/3 with a clamped helix structure similar to SN/1 and SN/2. The changes which were to be incorporated into SN/3 were to include:

1. Extra magnet pole pieces on the tube body so that shorter period magnet cells could be used in the large signal section of the tube.

2. The new cathode support structure was to be used in the gun.

3. The modified collector configuration was to be used to allow additional cooling of the collector.

In addition, by the time tube S/N3 was constructed, processed, and ready for test, the correct Alnico 8 magnets had been received and the special high voltage test power supply had been received. Further, platinum-cobalt magnets had been received for the short period cells in the large signal section so that uniform peak magnetic fields could be maintained along the full length of the tube. This tube, at last, would be tested under favorable conditions and it was felt that a meaningful magnetic field study could be carried out to determine the correct operating parameters.

Tests were just begun at the end of the quarter and measurements were made on the tube with magnet stacks of 1200 and 970 gauss peak field respectively.

Figure 6 shows the curves of power, gain and beam efficiency vs helix voltage for the peak field value of 1200 gauss. One curve was measured at a beam current of 100 mA. Insufficient RF drive power was available to drive the tube to saturation at the high voltage end of the curve. One point was measured at the 117 mA condition. A dotted line shows the general direction the curve would follow if additional data had been taken. At 117 mA, 90 watts of power output had been achieved at a beam efficiency of 22 percent.

Figure 7 shows a similar set of curves measured at 970 gauss peak magnetic field. When this magnet stack was assembled, sufficient time was taken to program the individual magnet values to give a stack value of 970±20 gauss. It is seen that a power output of 100 watts is exceeded at 115 mA and 3475 volts. Beam efficiency is 25.6 percent under these conditions. Power output as high as 120 watts was measured at 130 mA. Improved performance at lower magnetic fields is predicted.

Figure 8 shows a transfer characteristic measured at the highest power output point of Figure 7 at 3540 volts and 130 mA. This shows typical large overvoltage operation, where the small signal gain is considerably lower than the large signal gain. There is an 8 to 10 dB increase from small signal to large signal gain.

The fact that large signal gain is only 15.5 dB in SN/3 should not be a matter of major concern. In this experimental tube design, the input and output section of the helix are both of the same pitch. Hence the input is also operating under large overvoltage conditions or low gain per unit length and, therefore, is contributing little gain. The output section of the helix is always operating at 25 to 26 dB gain under maximum efficiency conditions. Under the conditions of Figure 8, the input helix section is actually operating with less than unity gain. It is not desirable to increase the input helix gain by designing the input section to operate under synchronous conditions at this point in the design sequence,

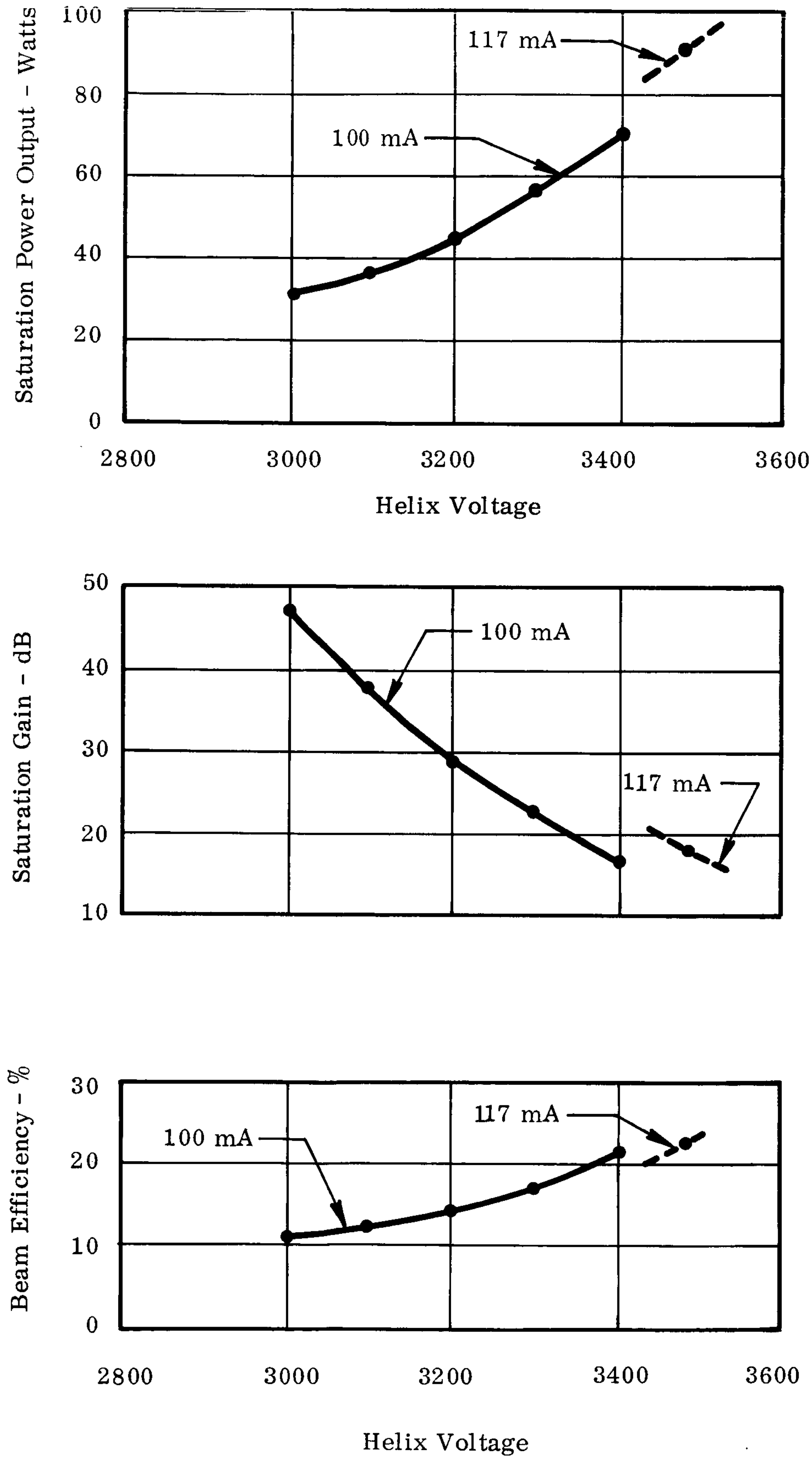

Fig. 6 - WJ-395 S/N3 performance with peak magnetic field of 1200 gauss.

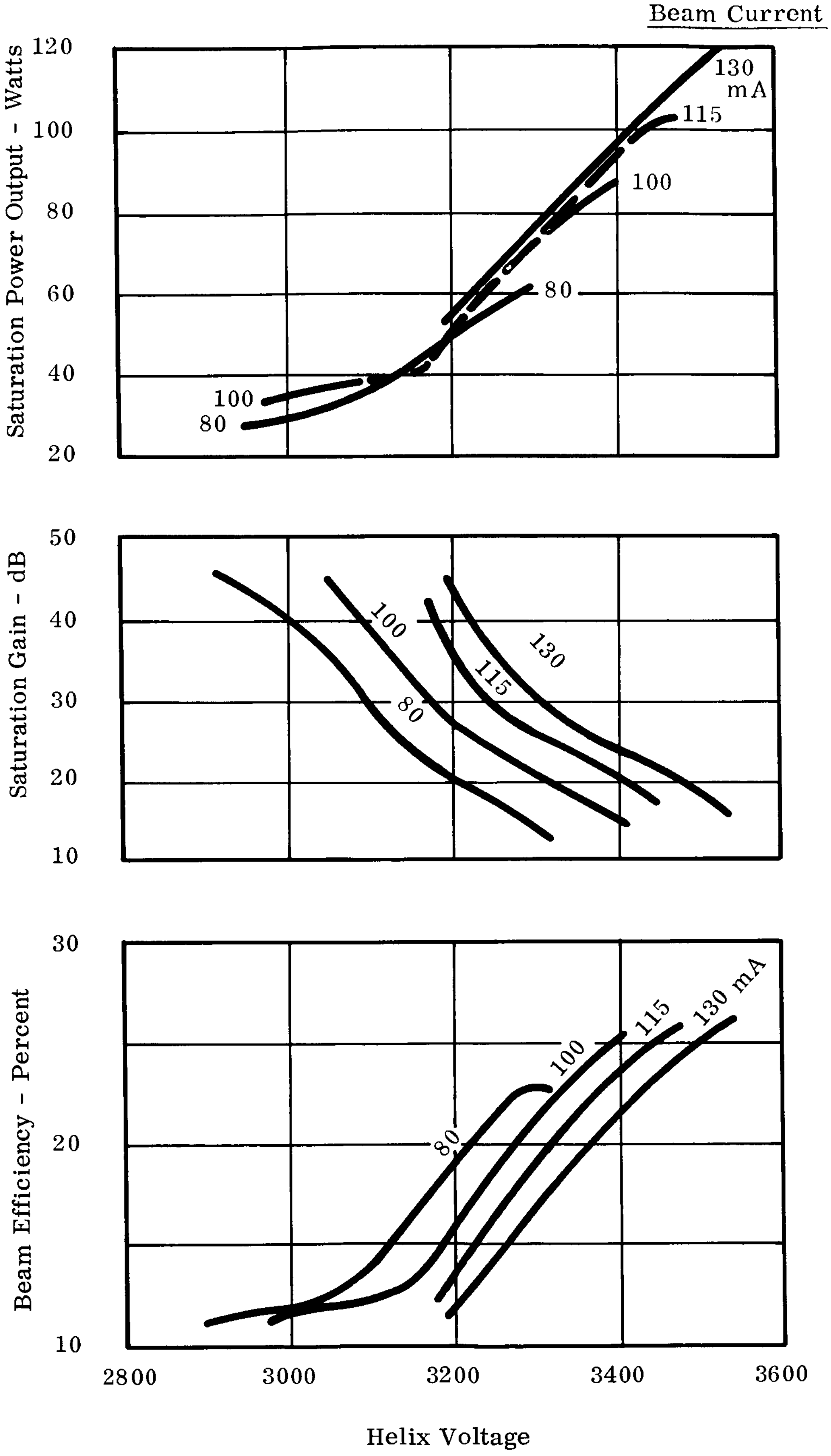

Fig. 7 - Power output, gain and beam efficiency on WJ-395, S/N 3, with peak stack magnetic field of 970 gauss.

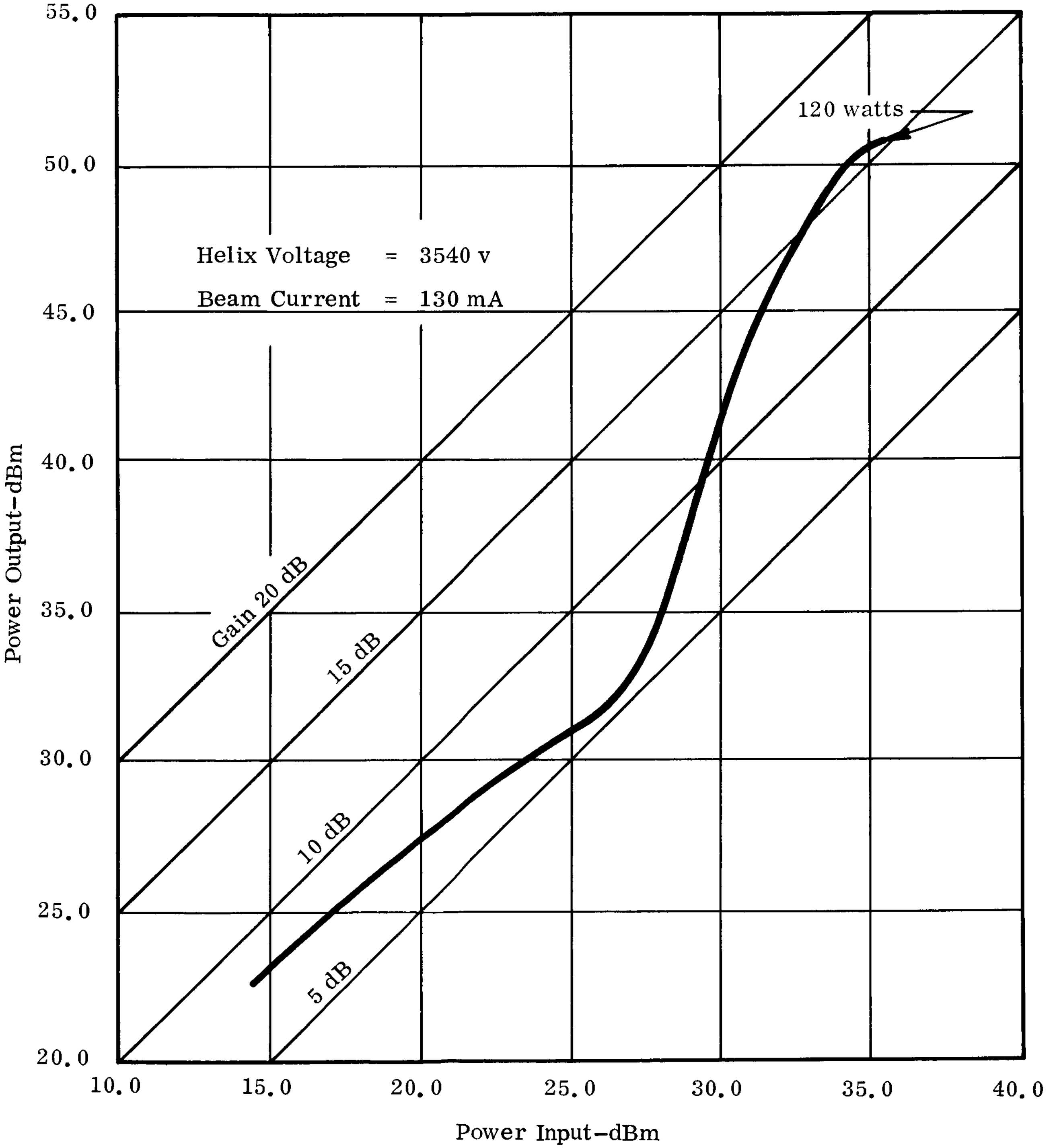

Fig. 8 - Power output vs power input for WJ-395, S/N 3, magnetic peak field of 970 gauss.

since the final output section operating conditions have not been chosen yet. The best thing to do is to design it to be electrically longer on the next tube, but still of the same pitch as the output section. This leads to less confusion in evaluating the gain contribution of this section of helix when choosing the ultimate design.

Figure 9 shows efficiency improvement and helix interception due to collector depression. Efficiency excluding heater power exceeds 31 percent for a helix interception of 9.0 mA. Power output under these conditions is 120 watts. This characteristic is expected to improve at lower peak magnetic field.

Figure 10 shows broadband performance under a fixed set of operating conditions corresponding to 120 watts output at 2.3 GHz.

Figure 11 shows a photograph of a typical tube ready for test.

Conclusions on WJ 395 SN/3

In this tube, even though tests are not complete, it is felt that we probably have the test vehicle necessary for the performance of the balance of the experiments of the program. Up to 120 watts of output power has been achieved, demonstrating the power handling capability of the structure. The efficiency is 4.5 percent below the interim tube design value of 30 percent, but this can likely be raised by further optimization of operating conditions and helix design. Gain can be improved on future tubes by modifying input helix design. Focusing shows promise of being good. Collector depressibility shows promise of being good. The question between glazed and unglazed (clamped) helices remains to be resolved. The general tube construction is not difficult.

Comparison of Efficiency Performance of Serial Nos. 1 through 3

Figure 12 shows a comparison of Serial Nos. 1, 2 and 3 for the two important parameters of saturation gain and saturated beam efficiency vs helix voltage measured at a beam current of 100 mA. It is clearly seen that tube No. 1 was totally different in both gain and efficiency performance from the others. This can be explained by excessive distributed helix loss. It is unfortunate that the tubes have to be compared at the magnetic field of 1200 gauss because the last data measured at a lower field indicated this value is too high.

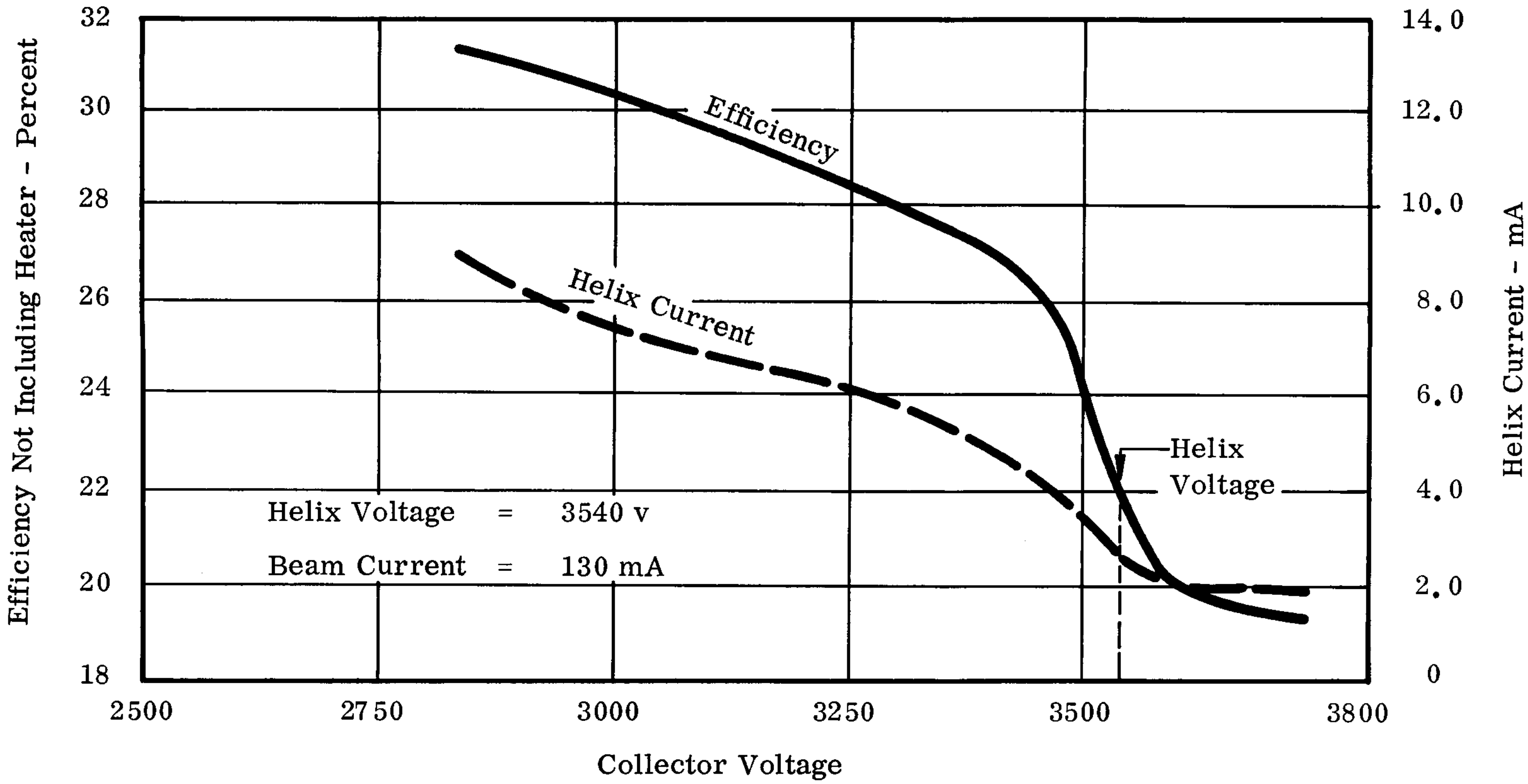

Fig. 9 - Collector depression characteristics at 970 gauss peak magnetic field of WJ-395, S/N 3.

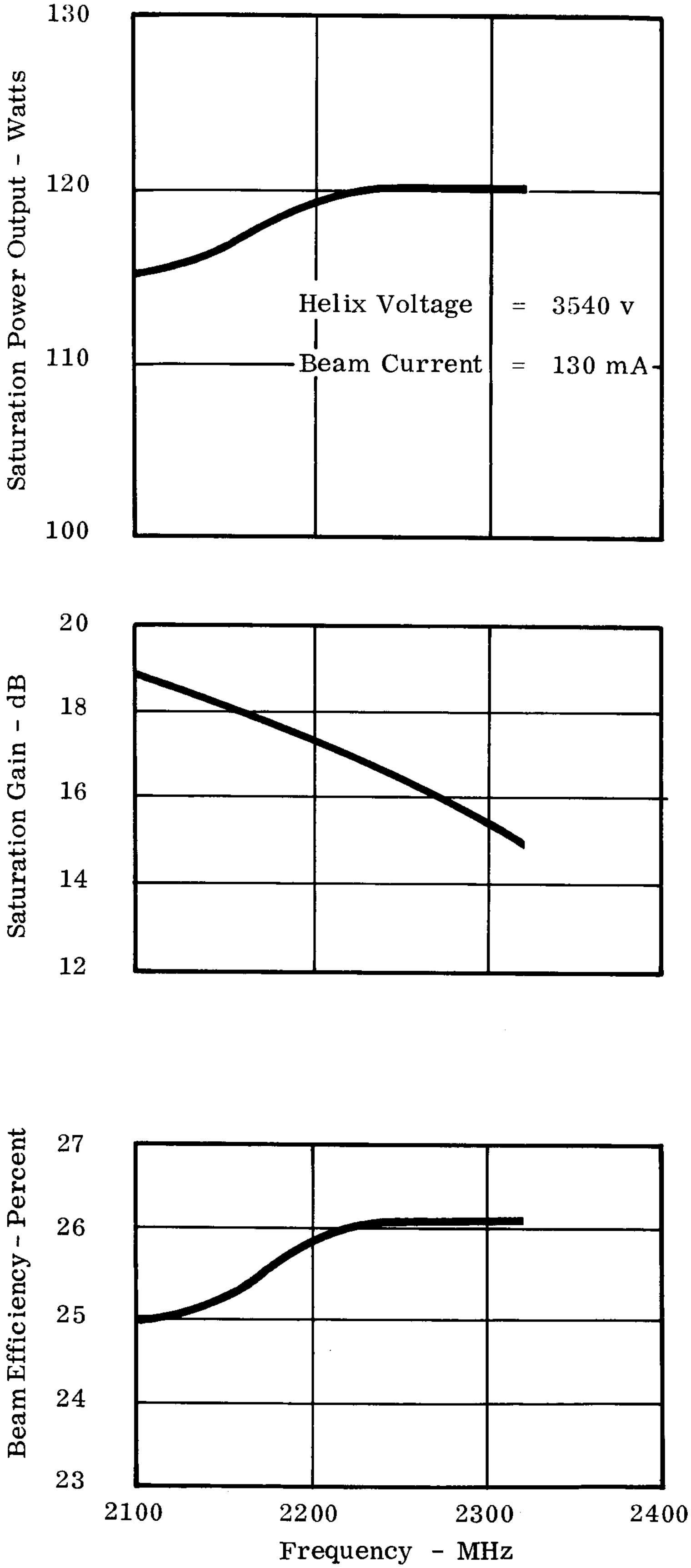

Fig. 10 - Broadband characteristics at fixed voltage and current conditions of WJ-395, S/N3.

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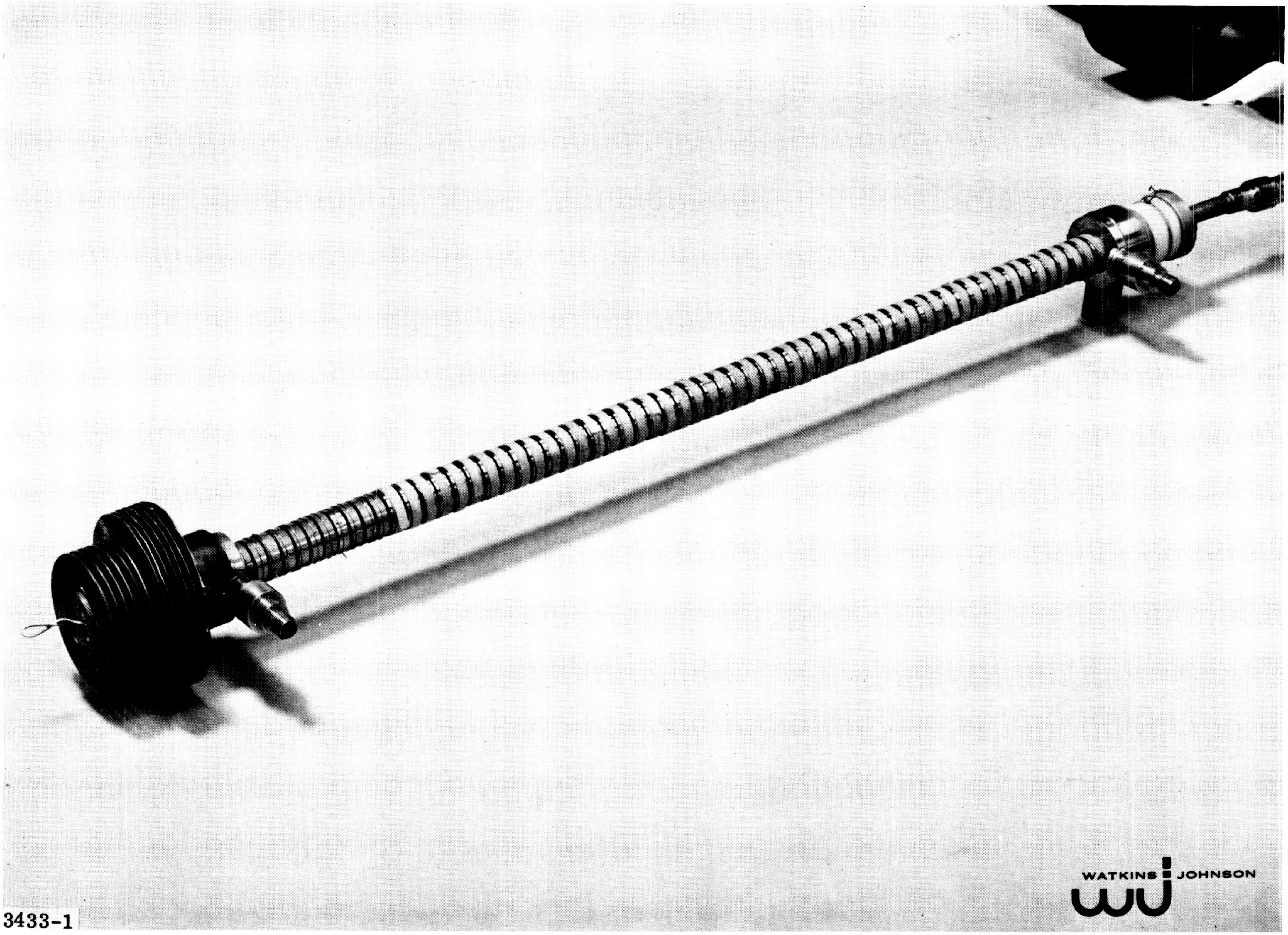

Fig. 11 - Photograph of a typical tube with magnets and collector cooler in place and ready for test.

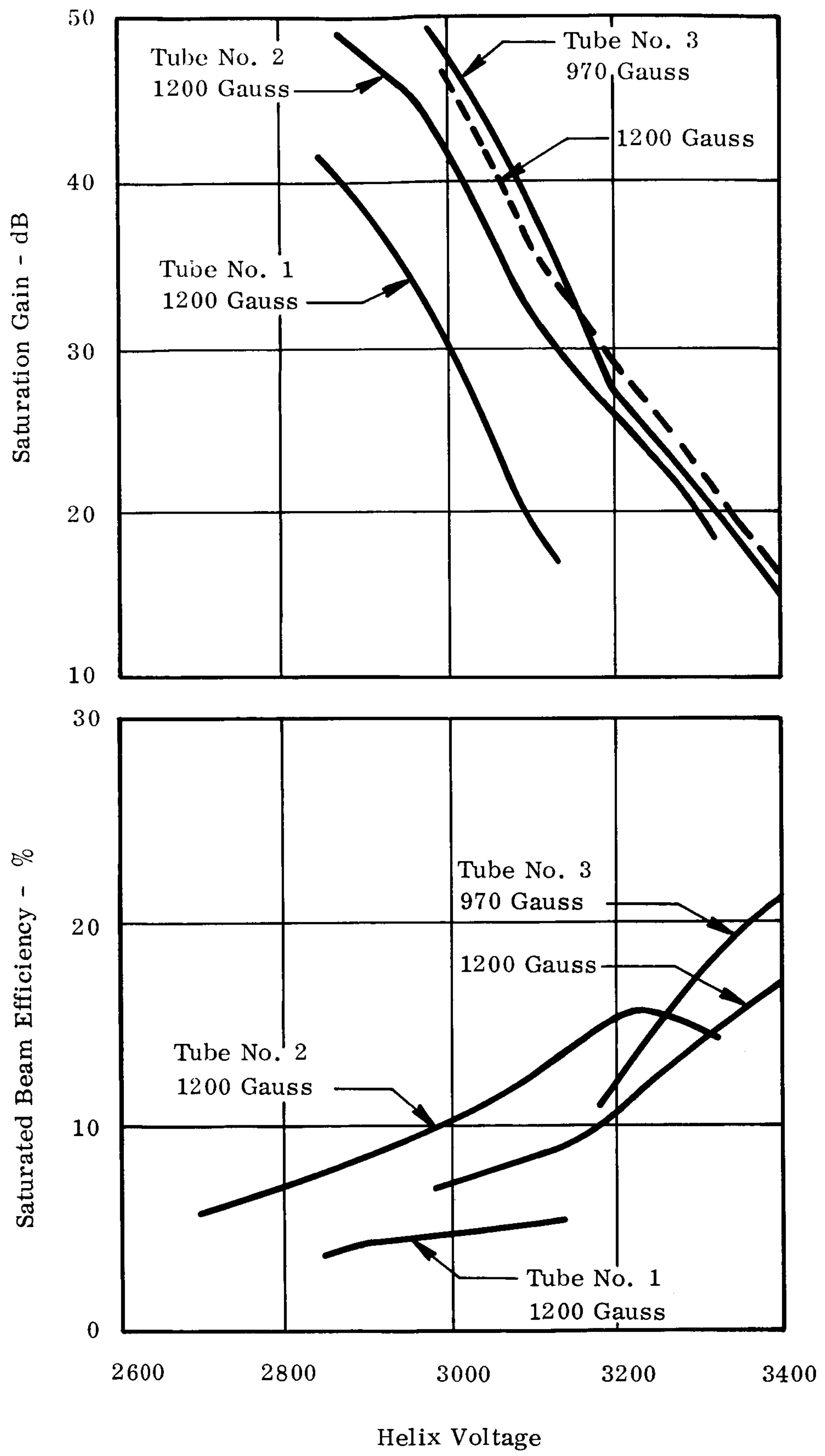

Fig. 12 - Comparison of saturation gain and beam efficiency of WJ-395 S/N 1, 2 and 3 at a beam current of 100 mA.

Ostensibly, Serial Nos. 2 and 3 have the same helix and beam design, yet SN/2 appears to be operating under conditions of higher effective overvoltage than SN/3. This conclusion is drawn because the gain of SN/2 is lower than that of SN/3 by 3 to 4 dB at any helix voltage and also the beam efficiency of SN/2 is higher by 3 to 5 percent for any voltage up to 3250 volts when the comparison is made at the same magnetic field value. The only known difference between the two is in the magnetic field period in the large signal section of the tube. It is not known whether this could account for this change in performance and will have to be determined in later experiments.

Items to be Accomplished During the Next Quarter

A glazed helix tube will be constructed to compare efficiency performance of glazed and clamped structures.

Tests will be made of the effects on gain performance with variations in the input helix design.

Encapsulation and thermal tests will be made to verify the mechanical support and heat transfer properties of the collector, collector insulation system and the capsule.

Construction of multi-helix tubes will begin.